Centennial-scale surface hydrology off Portugal during marine isotope stage 3: Insights from planktonic foraminiferal fauna variability

Maryline J. Vautravers[1,2] and Nicholas J. Shackleton[1,3]

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[1] The marine isotopic stage 3 (MIS3) at Ocean Drilling Program (ODP) Site 1060 (Gulf Stream) shows both sharp onset and end of interstadials, the existence of very short lived warm events during stadials, and points to differences in detail between the sea surface temperature (SST) record from the western North Atlantic and the atmospheric temperature record inferred from $\delta^{18}O$ in Greenland ice. Investigating MIS3 and obtaining comparable data from other locations appears crucial. The eastern Atlantic provides well-documented records of climate changes. We have selected a core from off Portugal and use it to examine Dansgaard/Oeschger events (D/O) at centennial-scale resolution (139 years on average between two data points). We have obtained a faunal data set for core MD01-2444, 37°N, 10°W, 2600 m water depth and use a group of species (*Globigerina bulloides* + *Globigerinita glutinata*) as a proxy of upwelling intensity driven by trade winds intensity changes. We tentatively relate the variation of this group to a North Atlantic Oscillation-like phenomenon (NAO) off Portugal. We observe that it resembles the rainfall index in the Caribbean as recorded at ODP Site 1002 (Cariaco Basin) which traces the Intertropical Convergence Zone (ITCZ) location through changes of terrigenous inputs. The driest intervals (ITZC to the south) at Site 1002 correspond to intervals of increased upwelling in MD01-2444 as well as the driest periods identified during stadials on similar cores in the area. Because the ITZC to the south is consistent with an El Niño–Southern Oscillation ($ENSO^+$) situation, our study suggests a positive correlation between ENSO-like conditions and NAO-like conditions at a millennial timescale. During interstadial intervals when increased wetness over Cariaco is recorded (ITCZ to the north) and the upwelling in MD01-2444 is decreased, we see from both SSTs and faunal tropical indicators that MD01-2444 site is warm. In addition, interstadials are equally warm through each so-called Bond cycle. This contrasts with the Greenland Ice Core Project (GRIP) record where interstadial peaks are successively cooler through each Bond cycle. This record confirms a link between tropical climate linked to ITCZ position and the climate of southern Europe at millennial timescales, in spite of showing a very good correlation with polar latitudes (GRIP) through $\delta^{18}O$ on *Globigerina bulloides*. In addition, because the warmest SSTs and the $\delta^{18}O$ on *G. bulloides* are so remarkably different, our work points to changes in seasonality as a strong control over the climatic pattern of the North Atlantic area and the marked influence of winter conditions.

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1. Introduction

[2] Our most detailed knowledge of millennial-scale variability, particularly during the last glacial, is largely based on the records obtained from the ice in Greenland [*Johnsen et al.*, 2001]. The atmospheric temperature record obtained through measurements of $\delta^{18}O$ in the ice cores reveals rapid and repeated events, indicating large swings in the climate of the Earth. Meanwhile, the marine climate record generally provide less detailed reconstructions, so that any oceanic record is viewed from the perspective of the Greenland record, which can be considered to be a "type section" for the climatic variability due to its decadal resolution.

[3] More recently, however, by focusing on very high resolution study (one sample on average every 123 and 23 years, respectively) in the North Atlantic, new records point to marginally contrasted climate patterns during the past 60 kyr [*Vautravers et al.*, 2004; *Peterson et al.*, 2000]. In addition to these oceanic records, continental data mainly obtained from archaeological remains and pollen series show a somehow moderated if not contrasting picture of the glacial climate [*van Andel*, 2003]. Mainly obtained from western Europe, these data indicate that marine isotope stage 3 was rather favorable in most places and only slightly colder and drier than the current interglacial except for short events, which were more extreme. As stressed by *Hemming* [2004], despite numerous new observations, our understanding of millennial-scale climatic variability still has

[1]Godwin Laboratory for Palaeoclimate Research, Department of Earth Sciences, University of Cambridge, Cambridge, UK.
[2]Now at British Antarctic Survey, Cambridge, UK.
[3]Deceased 24 January 2006.

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room for improvement especially as far as the timing and events duration as well as potential leads and lags in the system are concerned.

[4] When seeking a trigger mechanism for high-frequency variability during MIS3 outside the subpolar north Atlantic the global impact of a meteorological anomaly such as ENSO [*Lippsett*, 2000], which points to the tropics as a potential major player in the climatic system, should be considered. In particular, the key mechanism suggested by model results [*Bush and Philander*, 1998; *Cane*, 1998; *Clement et al.*, 1999] is that orbital parameters control the changes and variability of the seasonal distribution of heat and may therefore influence the global climate through its impact on ENSO and potentially the position of the ICTZ. The tropical climate plays a major role in the global water vapor budget. Studying the interaction between the tropics and middle temperate latitudes of Europe at a key location is relevant for improving our understanding of climate variability. Furthermore, as pointed out previously, tropical climate record such as the Cariaco Basin record of ITCZ motion during MIS3 [*Peterson et al.*, 2000], contrasts with the climate record from Greenland δ^{18}O ice [*Johnsen et al.*, 2001]. As a consequence, it is important to trace proxies of tropical climate outside the tropics.

[5] Since there is evidence that the polar front was moving north-south through time during the last glacial [*Zahn*, 1994], we expect the core site at 37°N to have been close to the polar front during some of the extreme cold events which punctuated MIS3 but also to have stayed under the influence of the tropical climate through surface current connections (i.e., the warm Azores Current) for a significant portion of this time interval. In addition, because polar to tropical planktonic foraminifera assemblages co-occurred in a latitudinal band around 35°–40°N during the Last Glacial Maximum (LGM), their presence suggests the absence of the North Atlantic Drift but the presence of a strong subpolar gyre [*McIntyre et al.*, 1976]. The faunal data generated at Site MD01-2444 will trace changing surface conditions at millennial timescale. Since at interannual and decadal timescales the core area is strongly under the control of the North Atlantic Oscillation (NAO) the aim of this study is to reexamine MIS3 at the edge of the subtropical world and to evaluate whether NAO-like patterns exist over longer Dansgaard/Oeschger (D/O) timescales.

[6] Records of various climate proxies from the Iberian margin have been produced in the past decades. These include stable isotope records obtained from planktonic species [*Duplessy et al.*, 1980], complemented by UK'_{37} ratio determinations [*Bard*, 2001], as well as planktonic foraminiferal census studies [*Cayre et al.*, 1999; *de Abreu et al.*, 2003] and studies of the pollen content of the same samples [*Roucoux et al.*, 2001; *Sanchez-Goni et al.*, 2002]. Others records have been obtained using stable isotope ratios measured on both benthic and planktonic species [*Shackleton et al.*, 2000; *Skinner et al.*, 2003], tracing deep-water changes in relation to climatic variability. All indicate the area as being of prime interest for paleoclimatic reconstructions and demonstrate the clear link between the surface oceanic record and the atmospheric temperature record derived from δ^{18}O in Greenland ice.

[7] The planktonic faunal variability has also been widely documented in the study area, based on both living planktonic assemblages [*Ottens*, 1991] and work on faunal assemblages for stratigraphic purposes in sediment cores [*Duprat*, 1983]. The first study demonstrated the relationship between the water masses and faunal assemblages, as well as the variations in faunal assemblages during the annual cycle in the northeastern Atlantic. In particular, the study of living planktonic foraminifera reveals the influence of frontal hydrologic zones between surface water masses on the delimitation of the faunal assemblages either living in the water column or found on the seafloor. For example, *Globigerina bulloides* and *Neogloboquadrina pachyderma* (*dex*) thrive within the North Atlantic waters, whereas *Globigerinoides ruber* and *Globigerina falconensis* live in subtropical waters south of the Azores front. More insights into planktonic associations are found in the recent work of [*Schiebel et al.*, 2002] on the Azores Current. Over the interval of MIS3, faunal assemblages were studied at relatively low resolution in MD95-2042 located nearby [*Cayre et al.*, 1999] and in two northern sites MD95-2039 and MD95-2040 [*de Abreu et al.*, 2003]. The latter study also obtained data for the lithic content of the samples in relation to ice rafted detritus events (Heinrich events; HE) known in the subpolar and the temperate north Atlantic area [*Heinrich*, 1988; *Bond et al.*, 1993; *Grousset et al.*, 1993]. The main finding is that HEs (particularly HE4) stand out as particularly cold in comparison to other D/O stadials [*Cortijo et al.*, 1997].

[8] Other work relevant to the understanding of the area, and that can be compared to the present results, are pollen records [*Roucoux et al.*, 2001; *Sanchez-Goni et al.*, 2002] and organic geochemical results from the Alboran Sea [*Cacho et al.*, 1999]. In particular, the study of *Sanchez-Goni et al.* [2002] shows that the pollen extracted from the Iberian Peninsula sediments can easily be interpreted in term of dry/wet episodes over the peninsula. These authors suggest further that dry stadials as seen from southern Europe were analogous to extreme NAO^+ like situations.

2. Study Area

2.1. Surface Circulation

[9] We have stressed the importance of atmospheric circulation changes in rapid climatic change. However, the ocean affects climate through its heat capacity relative to the surrounding continent in moderating daily seasonal and interannual temperature fluctuations.

[10] The western coast of the Iberian Peninsula is the northernmost limit of the seasonal eastern North Atlantic upwelling system. The site of core MD01-2444 is situated in very close proximity to a seasonal upwelling area [*Abrantes*, 1992]. The modern surface hydrography and nearby upwelling are governed by the intensity and changing direction of the offshore winds. In spring/summer as the Azores high intensifies and migrates north, the Portugal Coastal Current develops, driving strong upwelling and a cooling of the sea surface [*Wooster et al.*, 1976]. In contrast,

in winter the Azores high migrates south and decreases in intensity. This drives the northward flowing warm Portugal Coastal Counter Current, and leads to a reduction of upwelling and to warming over the core site. Figure 1, adapted from *Skinner and Shackleton* [2004], shows that surface waters are influenced by the descending branch of the North Atlantic Drift, also called the Portugal Coastal Current and by the Portugal Coastal Counter Current derived from the warm Azores current. This alternation makes the region very sensitive to past changes in surface circulation in connection with changes in the atmospheric circulation during rapid climate changes.

2.2. Climatology of the North Atlantic Area Close to the Iberian Peninsula

[11] The climate regime over the Iberian Peninsula, as well as of substantial parts of western Europe is mainly governed by the position of an atmospheric center of high pressure located over the Azores (the Azores high) and its latitudinal motion and intensification through the annual seasonal cycle. As a result this area is very strongly under the influence of the meteorological North Atlantic Oscillation (NAO) anomaly [*Hurrell*, 1995]. The NAO index measures the anomaly as the difference in atmospheric pressure between the Iceland low and the Azores high. The NAO is said to be positive (NAO^+) when the Azores high is reinforced. In this situation, the key observations are that the westerly winds become stronger, resulting in the Gulf Stream trajectory relocating northward, and the northern part of Europe becomes anomalously wet and milder than usual in winter. In contrast, the southern part is anomalously dry and cold. The NAO also affects the sea ice coverage in the northern North Atlantic, which in turn impacts on ocean convective activity [*Dickson et al.*, 1996]. Off Portugal, NAO^+ phases are associated with reinforcement of the summer circulation pattern, and therefore correspond with reinforcement of the upwelling through increased NE trade wind forcing. Interestingly, the NAO^+ also corresponds to high phases of the Arctic Oscillation (AO^+), which is characterized by an enhancement of the polar high over the north polar area. In the opposite situation (NAO^-) the westerly winds are weaker, the Gulf Stream is located further south, northwestern Europe is dry whereas southern Europe is wet, and in the studied area the upwelling is reduced as warm conditions influenced by the Azores Current prevail [*Dickson et al.*, 1996].

[12] In the tropics, climatic conditions are mainly governed by the alternation of contrasting rainy (warm) and dry (colder through the action of SE trade winds) seasons that trace the motion of the ITCZ. At millennial timescales in the Pacific, salinities were higher at times of high-latitude cooling and were lower during warm interstadials; the implied pattern and amplitude of fluctuations indicate changes analogous to modern ENSO modes [*Stott et al.*, 2002]. In the Atlantic, the seasonal motion of the ITCZ, over the Caribbean Sea as well as the northernmost coast of South America follows the summer heating of the corresponding hemisphere. In addition, at interdecadal timescale, the reinforcement of warm and rainy or cold and dry season is also under the control the ENSO phases,

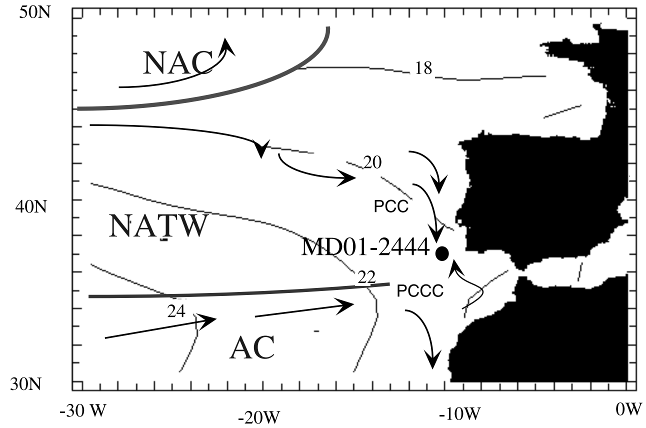

Figure 1. Surface currents off Portugal Costal Counter Current (PCCC), Portugal Costal Current (PCC) and location of core MD01-2444 (37°45′N, 10°W; 2600 m; average sedimentation rate over the studied interval is 23.2 cm/kyr). Isotherms are August SST at 10 m water depth. Levitus 1994 database, Lamont-Doherty Earth Observatory data source.

ENSO being associated with drier than average seasons over the Caribbean based on modeling results [*Giannini et al.*, 2001] and observations. A number of studies have suggested that a southward migration of the ITZC was linked to cooling on the North Atlantic over various timescales [*Black et al.*, 1999; *Peterson et al.*, 2000; *Schmidt et al.*, 2004]. Model results suggest that the strength of the Meridional Overturning Circulation (MOC) is reduced in intensity when the position of the ITCZ migrates to the south [*Schiller et al.*, 1997]. Therefore large-scale meteorological conditions that are reinforced over the western Atlantic tropical area might later directly affect Europe via a lagged warming of the North Atlantic via heat transport by warm surface currents such as the Gulf Stream and its two branches, the North Atlantic Drift and the Azores Current, or indirectly also because of the changing regime of the MOC.

[13] As a consequence, and despite a lack of clear temporal correlation [*Giannini et al.*, 2001] between the two meteorological indices, ENSO and NAO can still provide useful templates for explaining paleoclimatic changes. However, the NAO influence should not be overstated in the North Atlantic area since more complex interplays with ENSO are known to affect the climate of southern Europe. For example, ENSO and NAO phenomena both influence rainfall in Iberia, and their effects coexist at different temporal and spatial scales [*Rodo et al.*, 1997]. ENSO oscillation signals have been observed in the analysis of records of the past century of rainfall from stations spanning the Iberian Peninsula. In addition and despite evidence that the western part of the peninsula is more generally under the influence of NAO in winter, the eastern part is more under the influence of ENSO, particularly in spring and autumn. *Rodo et al.* [1997] also concluded that over the last century the NAO influence did not change, while ENSO influence (through increased rainfall) has both

intensified during the second half of the century and extended to the whole peninsula. By studying faunal assemblages in core MD01-2444 we expect to be able to track the fluctuation of tropically associated influences at millennial timescale during MIS3.

3. Methods

3.1. Material

[14] The coring site is located at 37°N, 10°W and at 2600 m water depth beneath the eastern limb of the subtropical gyre (Figure 1). The core was retrieved during a cruise of R/V *Marion Dufresne II* in 2001 using the Calypso giant piston corer.

3.2. Stable Isotopes

[15] The measurements of the stable isotopes of oxygen and carbon were performed in Cambridge on a SIRA mass spectrometer. Analyses were made on samples consisting of 30 specimens of *G. bulloides* in the 300–355 μm size fraction. Analytical procedures and reproducibility are described by *Shackleton et al.* [2000].

3.3. Planktonic Foraminifera Fauna

[16] The identification of the planktonic foraminifera species in the greater than 150 μm size fraction is based on the work by *Kennett and Srinivasan* [1983]. The faunal counts were carried out on representative split subsamples containing at least 300 whole specimens.

3.4. Ice-Rafted Detritus

[17] The lithic counts were performed on the same split fraction used for faunal identification. We recognize the presence of some detrital carbonate grains but the most commonly found lithics were quartz. We express the concentration of total lithics as the number of lithic grains per gram of dry sediment.

3.5. Faunal SSTs

[18] For Site MD012444 the SSTs were calculated using the Simmax method [*Pflaumann et al.*, 2003] with the selection of five best analogs using a database containing 947 surface samples from the North and South Atlantic We used a dissimilarity coefficient threshold of 0.85 for our analysis.

4. Age Model

[19] The age model (Table 1) is developed by correlation between the δ^{18}O record of *G. bulloides* in core MD01-2444 and the ice core δ^{18}O record [*Johnsen et al.*, 2001] in an analogous way to *Shackleton et al.* [2000]. Because it appears that the brief interstadials at the base of MIS3 are not recorded in the δ^{18}O record but are instead recorded by the percent of the warm species *G. ruber*, we made use of this variability to select one additional control point. We used the timescale developed by *Shackleton et al.* [2004] for Greenland Ice Core Project (GRIP). In order to compare the results obtained for core MD01-2444 with those obtained at ODP Site 1060 [*Vautravers et al.*, 2004] as well as for the Cariaco Basin record of [Fe] at ODP Site 1002 [*Peterson et al.*, 2000] these other records have also been put on the timescale of *Shackleton et al.* [2004].

5. Results

5.1. Isotopic Results

[20] The planktonic δ^{18}O stable isotope record obtained on *G. bulloides* (Figure 2b) is similar to that obtained by *Shackleton et al.* [2000] from nearby core MD95-2042 and shows regular oscillations of surface properties than can easily be correlated to the Greenland ice core record, providing the basis for the stratigraphy as explained above. It is important to note that the similarity between the two sediment records attests to their quality and confirms that it is possible to duplicate marine results with good reliability in a similar manner to that previously achieved for ice cores.

5.2. Faunal Results

[21] Some key species or groups of species can be used as environmental and climatological tracers. This work attempts to do this. We examine the fluctuations of the polar species *N. pachyderma* (*sin*) (Figure 2c). This species has been used extensively within the North Atlantic as a proxy for climate cooling [*Ruddiman et al.*, 1986; *Bond et al.*, 1993]. At present, this species is absent from plankton tows [*Ottens*, 1991] and surface sediments [*Pflaumann et al.*, 2003] (Simmax database) collected in the study area. Downcore the percentage of this species shows three main episodes of similarly high values (50–60%) coinciding with HE6, HE4 and HE3. The extreme maximum (80%) is found during HE4 at an age of 39.5 kyr. The relative strength of these three major stadials as depicted by *N. pachyderma* (*sin*) off Portugal decreases with younger age. This is an unexpected finding, as we would expect the colder events to be found toward the end of MIS3 as a result of glacial advance and the suspected southward shift of the polar front [*Zahn et al.*, 1997]. In addition to these major stadial events, *N. pachyderma* (*sin*) is also present in three other stadials with similar high abundances of about 10–25%; during HE5, during the stadial before Greenland Interstadial (GIS)14 and during the stadial following GIS8. For this last event we note that the severity of this stadial was already apparent from the record obtained at ODP Site 1060 [*Vautravers et al.*, 2004] and also in the Alboran Sea record of [*Cacho et al.*, 1999], pointing to a North Atlantic-wide event at the time. Finally, during the other D/O stadials this species is consistently represented by only low percentages, less than 10%. However, during each of the successive intervals GIS17 to 13, GIS12 to 9 and GIS8 to 5, the influence of polar water on the core site decreased from beginning to end, so that polar fauna are not more abundant as the LGM approaches (see dotted arrow in each Bond cycle). This pattern of fluctuation contrasts with what would be expected on the basis of the GRIP record, where stadials are comparatively cold and interstadials progressively become cooler within each individual Bond cycle (bc on Figure 2). Hence this record contradicts the idea of a progressively southward moving polar front through the last glacial advance and indeed seems to show a northward displacement of this feature over the interval. Beyond this general observation, it is obvious that minor stadials are not

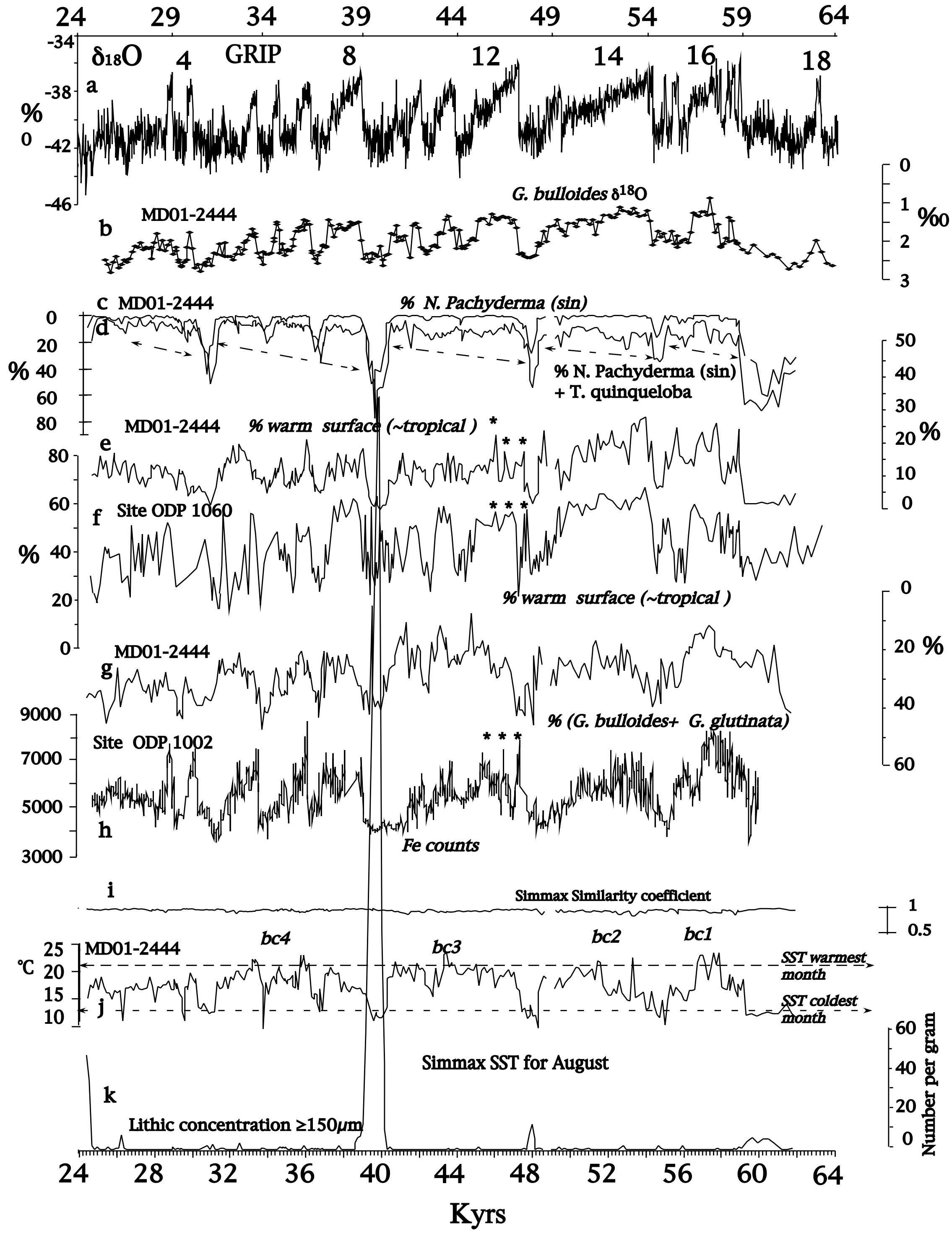

Figure 2. (a) The GRIP $\delta^{18}O$ record, on the timescale of *Shackleton et al.* [2004]. (b) *G. bulloides* $\delta^{18}O$ at MD01-2444. (c) Percent *N. pachyderma* (*sin*) in reversed scale at MD01-2444. (d) Percent *N. pachyderma* (*sin*) + percent *T. quinqueloba* in reversed scale at MD01-2444. (e) Percent of warm surface species at MD01-2444 species group as from *Vautravers et al.* [2004]. (f) Percent of warm surface species at site ODP 1060. (g) Percent of productivity related species *G. bulloides* and *G. glutinata*. (h) [Fe] from XRF measurements at Site ODP 1002. Data are from *Peterson et al.* [2000] transferred onto the *Shackleton et al.* [2004] age model. [Fe] is used as a rain index over the Cariaco Basin. (i) Simmax similarity coefficient. (j) Sea surface temperatures from Simmax method. Dashed lines are for present August and February SSTs, bc is for Bond cycle. (k) Number of lithics (IRD) over 150 μm size per gram of dry sediment.

Table 1. Age Control Points and Corresponding Horizons in the GRIP Ice Core

Age,[a] kyr B.P.	Depth in Core, m	Horizon in GRIP
14.8	2.595	
24.1	5.919	
29.00	6.975	base GIS3
29.79	7.29	top GIS4
30.06	7.35	base GIS4
33.09	8.07	top GIS5
33.44	8.205	base GIS5
34.26	8.415	top GIS6
34.64	8.565	base GIS6
35.43	8.85	top GIS7
36.29	9.14	base GIS7
37.19	9.47	top GIS8
39.00	9.87	base GIS8
40.83	10.335	base GIS9
42.10	10.605	base GIS10
43.87	11.085	base GIS11
47.24	11.815	base GIS12
48.55	12.18	top GIS13
54.29	13.195	top GIS14
57.87	13.98	base GIS16
58.62	14.185	base GIS17a
59	14.305	base marine isotope stage 3
63.17	14.725	base GIS18
70.75	15.49	base GIS19

[a]From *Shackleton et al.* [2004].

equally individualized during each Bond cycle. For example, stadials during bc3 are not well developed in contrast to those during bc4. Indeed, the one between GIS7 and GIS6 seems to be ''missing'' in the faunal record though the event is clear in the $\delta^{18}O$ record. Such a contrasted variability between stadials and interstadial is clearly recorded in the Cariaco rain index record (Figure 2h), whereas the $\delta^{18}O$ GRIP record (Figure 2a) shows less indistinct cold stadials during one or the other bcs.

[22] Because high percentages of *Turborotalita quinqueloba* are found south of Iceland [*Pujol*, 1980], and its maximal abundance has also been recognized as being associated with the polar front [*Cayre et al.*, 1999; *Wright and Flower*, 2002], the fluctuations exhibited by the combined abundances *N. pachyderma* (*sin*) and *T. quinqueloba* (Figure 2d) confirm that the polar front was distant from the site for most of the time. Variations of this group also indicate the existence of additional cold climatic events during the longest interstadials like GIS14, or between GIS10 and GIS9, that were not revealed by percentage of *N. pachyderma* (*sin*) alone.

[23] We now, examine the group comprising the warm surface species (Figure 2e) as defined in the Gulf Stream area by *Vautravers et al.* [2004] and that includes only tropical mixed layer dwelling species. Most of these species live in warm tropical and subtropical waters found south of the Azores front, and therefore show the influence of tropical water originating in the Gulf Stream on the core site after the upwelling season. This group demonstrates a remarkable variability, displaying all of the features (GIS and GS) seen in the GRIP record, although some differences are noticeable. Since this tropical group exhibits well-defined stadials and sharp changes at both the onset and end of interstadials it shows a closer resemblance to GRIP temperature record than the group of polar species. This can be interpreted to support a tropical influence over the Greenland record and indicates that the Greenland $\delta^{18}O$ record is likely not to be simply influenced by the extreme position of the polar front within the North Atlantic oceanic area.

[24] We also find that variations in the group of tropical species record additional but smaller events and at a higher frequency than D/O. This is visible in some of the longest interstadials, for example during GIS8 (see events marked by asterisks on Figure 2), as well as GIS14. Despite the uncertainty in the precise timing of these events between records they seem to be recorded by the tropical rain index in the Cariaco Basin [*Peterson et al.*, 2000], in the cave record of [*Genty et al.*, 2003] and by the arboreal pollen record of a nearby core off Portugal core [*Roucoux et al.*, 2001]. The fluctuations of the warm group point to the tropical influence being at a minimum during HE6, HE5, HE4, HE3, but also during five other episodes that are marked by prominent decreases at the core site. These are found in all the other stadials, but three of the better marked are found after GIS8, GIS15 and GIS14.

[25] We note that the earlier part of MIS3 is the richest in tropical species, supporting the idea that the early part of MIS 3 was the warmest part of this isotopic stage. It is quite remarkable that this situation occurred despite this interval being also the richest in polar species a result that perhaps indicates maximum seasonal contrast during the first part of MIS3. This would have happened in apparent contradiction to the SSTs not reaching maximal value during this time as intense upwelling conditions and a weak polar influence would draw down the calculated SST (Figure 2j) despite the warm postupwelling conditions. The warming after upwelling would have influenced the vegetation on the nearby continent through heat and moisture transfer, explaining why pollen spectra from this area exhibit a good similarity to the GRIP atmospheric temperature record and why they also resemble to the tropical assemblages, as is visible from the percent of arboreal pollen during GIS14 [*Roucoux et al.*, 2001]. The interval from GIS12 to 9 (bc3), in comparison to other bc intervals, is poor in tropical species, which to a relatively weak postupwelling warming. This is in agreement with *Roucoux et al.* [2001], who report a low tree development in this Bond cycle in comparison to the bracketing cycles. In contrast, the succeeding GIS8-5 interval appears comparatively rich in tropical species and the sustained warm conditions appear to persist even after the end of GIS5. This feature is also recorded elsewhere in the area [*Roucoux et al.*, 2001], in the Alboran Sea [*Cacho et al.*, 1999], in the Santa Barbara Basin [*Behl and Kennett*, 1996], in the western tropical Atlantic (ODP Site 1060 plotted in Figure 2f, for comparison), and is very consistent with the Cariaco [Fe] record [*Peterson et al.*, 2000]. In addition, with regard to each succeeding Bond cycles, we cannot distinguish between their end and their beginning in terms of their percentage of warm species. Therefore it appears that at the northern edge of the subtropical area the postupwelling conditions were relatively warm and unchanged throughout MIS3. It is puzzling that

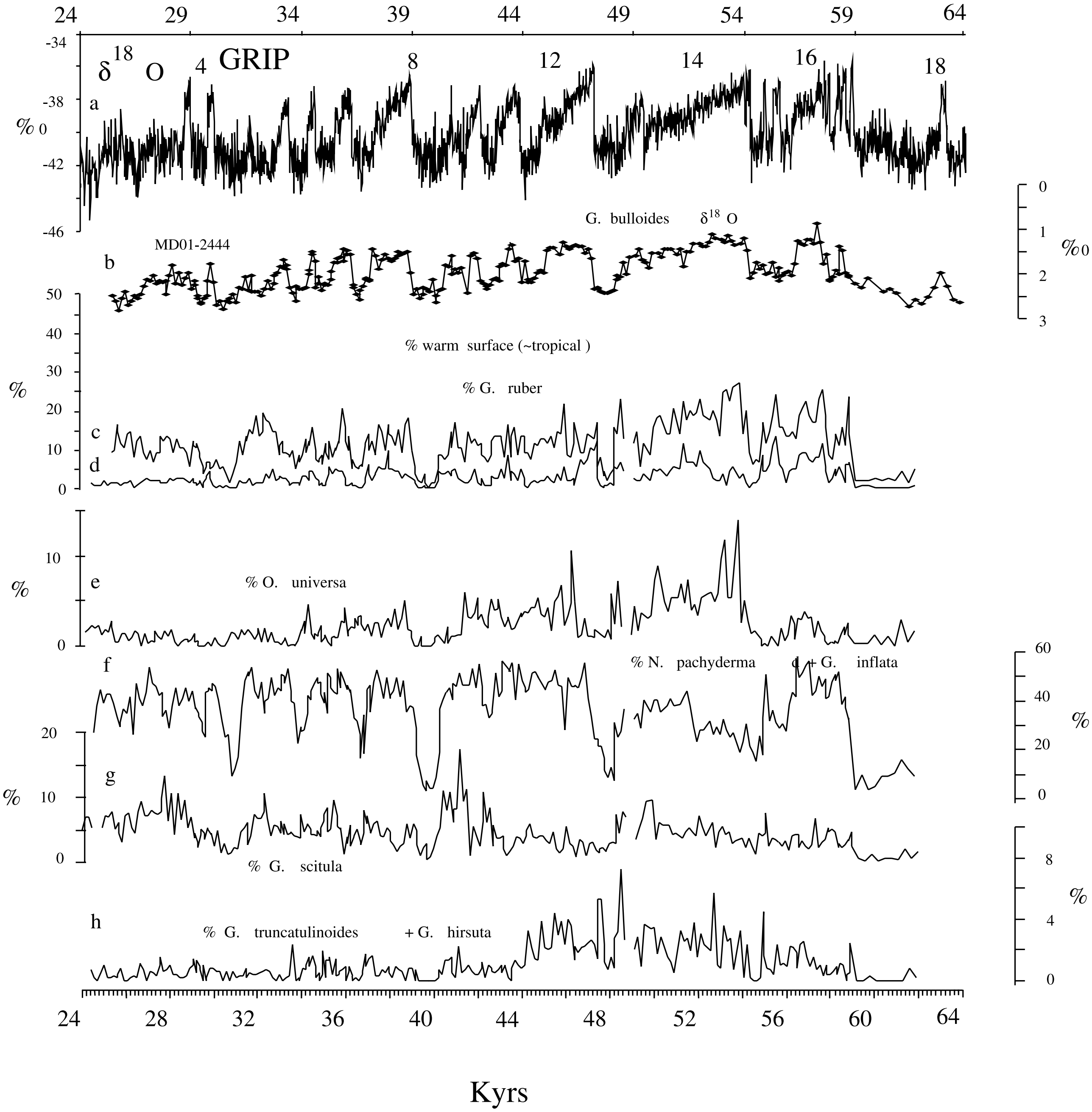

Figure 3. (a) The GRIP $\delta^{18}O$, on the timescale of *Shackleton et al.* [2004]. (b) *G. bulloides* $\delta^{18}O$ at MD01-2444. Faunal data at site MD01-2444. (c) Percent warm surface species at MD01-2444. Species are grouped according to *Vautravers et al.* [2004]. (d) Percent *G. ruber*. (e) Percent *O. universa*. (f) Percent *N. pachyderma* (*dex*) + *G. inflata.* (g) Percent *G. scitula.* (h) *G. truncatulinoides* + *G. hirsuta*.

these percentages are high during GIS15, GIS13, GIS9 and GIS5, all GIS intervals that are toward the end of each Bond cycle. This may suggest an increasing influence of tropical water via reinforcement and/or a warming of the Azores Current at least on a seasonal scale during these intervals. This finding is supported by the high percent *Globoratalia scitula* (Figure 3f) found toward the end of each Bond cycle, high percentages of which are today associated with the Azores front [*Schiebel et al.*, 2002] (Figure 1). Such warm conditions even as a seasonal feature via the Azores current and detected off southern Portugal could be relative to the subtropical warming that is proposed to have happened as a consequence of the reduction of the meridional overturning circulation (a marked cooling of the high latitudes is associated to the heat being stored in the subtropic) [*Huls and Zahn*, 2000; *Ruhlemann et al.*, 1999]. Within the group of warm species *G. ruber* is a frequent and major contributor (Figure 3d).

[26] Changes in the relative contribution of *G. ruber*'s within warm surface group may also point to some hydrological peculiarities. *G. ruber*'s percentages are high during GIS17 to GIS15 (maximum in GIS15), at the onset of GIS12 and GIS9, as well as during and at the end of GIS8 and GIS7. As a result, with respect to their tropical faunal content, the two long GIS14 and GIS12 have very different onsets. The greatest proportion of warm species at the beginning of GIS14 is made up of *Orbulina universa* (Figure 3e), which can tolerate cooler SST than *G. ruber*. The opposite is observed at the beginning of GIS12. This suggests that the first part of GIS14 was colder than that of GIS12 because the upwelling was being sustained for a longer time through the year during the first part of GIS14 compared to GIS12. Again, this should be put into the perspective of the differences observed between these two intervals in the Cariaco Basin (Figure 2h). Indeed, the onset of GIS12 is characterized by a major wet pulse that seems to correspond to an increase in the percent tropical fauna at ODP Site 1060 (Figure 2f). In contrast, the first part of GIS14 is represented by numerous rapid fluctuations (dry/wet), but of lesser amplitude than the three large fluctuations recorded in the first part of GIS12. During interstadials, the other main contributing tropical species is *G. falconensis*. Like *G. scitula* it increases during each Bond cycle from beginning to end (up to 12% during GIS5). Although this species is sometimes mistaken for *G. bulloides*, it is considered to be a tropically adapted symbiont-bearing form of *G. bulloides* [*Hemleben et al.*, 1989] so its increased abundance may suggest warm condition. However, this species was found to be more abundant in the Arabian sea under the influence of the NE (winter monsoon), which generates cooling and mixing as well as enhanced productivity as a result of the erosion of the nutricline [*Schulz et al.*, 2002]. Perhaps the species traces a similar winter phenomenon off Portugal with an increasing influence during the course of individual bc intervals.

[27] Next, we examine the group made up of *G. bulloides* and *Globigerinita glutinata* (Figure 2g). *G. bulloides* is traditionally considered to be an upwelling indicator species [*Prell*, 1984], and particularly in the northeastern subtropical Atlantic [*Chapman et al.*, 1996]. It is also abundant in subpolar waters (north of 48°N), which besides being colder than tropical waters are also richer in nutrients, including silicon, which is used to form the skeletons of diatoms on which nonspinose planktonic foraminifera like *G. glutinata* feed [*Hemleben et al.*, 1989]. The study of the living planktonic fauna in the eastern Atlantic has confirmed that *G. glutinata* prefers productive environments [*Ottens*, 1992]. High percentages of this opportunistic species are observed in relation to surface current eddies that help to increase the nutrient input to the mixed layer, as is the case in the slope water north of the Gulf Stream [*Olson and Smart*, 2004] and in cyclonic Atlantic water eddies occurring within the Caribbean Sea [*Schmuker and Schiebel*, 2002]. This species was also recognized off Chile as a tracer for changing paleoproductivity [*Mohtadi and Hebbeln*, 2004]. We have used the group of these two species as a straightforward indicator of changing productivity in core MD01-2444, and thus of changing trade wind intensity over the area. At present intervals of increased trade winds are positively correlated to periods of NAO+. The percentages of this group range between 10 and 50% (Figure 2g). Minimal values are systematically found during interstadial times, and higher during stadial times, especially high during HEs. There are seven maxima (with values around 45–50%) before HE6, before GIS14, HE5, HE4 after GIS8, before GIS5 and between GIS4 and GIS3. This confirms the observation of *Sanchez-Goni et al.* [2002] based on pollen counts at nearby site MD95-2042, who interpret stadials as dry and cold and corresponding to reinforced NAO+ like conditions. We note that HE6 is unusual because it is not rich in upwelling species. The minima in upwelling indicators are found during GIS16 and during three events at the end of GIS12, GIS11 and GIS10. With respect to Bond cycles, we find that the different bcs are different: bcl exhibits the absolute longest minima during GIS16; bc2 shows the average highest values of this indicator but this cycle is marked by the absence of any major increase during stadials of the interval; bc3 shows extremely reduced interstadial upwelling conditions but well developed stadials (increasing in succeeding stadials). This situation is in sharp contrast with the preceding bc2. Finally, bc4 shows very well individualized D/O cycles in particular due to stadial conditions being very pronounced. However, during bc4, the percentage for the group only reached the values found during HEs in the preceding bc at two occasions. We note here that the resemblance between the curve for this group of species and the GRIP δ^{18}O record is not very good for this interval, especially after GIS5. This contrasts with the sharp resemblance to the Cariaco [Fe] record (a rain index record) good over MIS3, and that is even better during this last interval of MIS3. As for the preceding cycle, GISs during this last Bond cycle are well characterized by stable (weak) conditions of the upwelling indicator but which also increases toward younger stadials. This group might indicate a general trend toward increasing NAO+ index from the end of GIS12 to the end of MIS3.

[28] Other abundant species are *Globoratalia inflata* and *N. pachyderma* (*dex*) (Figure 3g), which we have grouped together. In fact, this group is the most common group of species on the site with the sum of both species ranging between 0 and 70%. This group can be interpreted to represent the North Atlantic Sub Polar Water (NASW) at the core site [*Ottens*, 1992], with high abundances indicating the absence of a strong seasonal thermocline. On that basis, for example, GIS14 is the time when the seasonal thermocline was the most developed. This confirms our observation that this interval of time was characterized by relatively strong upwelling compared to the other GIS.

[29] *Globorotalia truncatulinoides* and *Globorotalia hirsuta* are grouped together (Figure 3f). *G. truncatulinoides*, is present with maximum percentages of 5%, but only during the interval 59–44 kyr and before 63 kyr, while *G. hirsuta* is represented only during GIS14 and the beginning of GIS12 with even lower percentages (<3%). These two species are known to be deep dwellers that need good mixing in order to develop. The fact that they are found in greater abundance during GIS14-12 indicates that this time

interval was characterized by a maximum mixing at the same time as the seasonal thermocline was pronounced. However, because the deepest dweller *Globorotalia crassaformis* is absent from the samples, the mixing of the water column certainly did not exceed 200–300 m depth.

[30] In the Globorotalia group, we have found *G. scitula* to be the most abundant of the three species (up to 17% in GIS13 but more generally around 5%). This species (as noted earlier) displays an unexpected abundance pattern, with increasing values toward the end of each Bond cycle just before the onset of the following HE event. We have interpreted this as representing an increased influence of the North Azores front water on the site of core MD01-2444. This suggests, that the front might have been displaced to the north with respect to its present position, but this would need to be confirmed by other proxies. Peaks in the abundance of this species are particularly marked during GIS13, GIS11–GIS10, and GIS5.

5.3. Faunal SST Results

[31] Before discussing the results of the SST estimates, we need to make several general remarks about the possible significance of these results and their statistical validity for the whole of MIS3 and the details of each D/O fluctuation. We only present the calculations from faunal estimates for the month of August, as generated by the Simmax method [*Pflaumann et al.*, 1996]. These estimates generally refer to the warmest month within the North Atlantic surface water. At present, on the core site, the warmest SSTs are reached in August (attaining 22°C), but this might not have been the case in the past if the area was affected by a stronger seasonal upwelling that was extended later in the year. As a result, we must consider that these reconstructed SSTs correspond to the SST of the warmest month whenever this occurs at the end of the upwelling season. The present coldest SSTs occur during February, reaching 13°C.

[32] The similarity coefficient (Figure 2i) gives a quantitative estimate of the resemblances between the associations found in the core samples and those in the database. We have selected a threshold similarity level of 0.85 for the Simmax procedure. All but three samples find the five requested analogues within this limit. These three samples are one at 48.9 ka during GIS13 that cannot find any analog, and two during GIS14 at 53.19 and 53.36 ka that find only two analogs. The first sample is characterized by its unusual richness in *G. scitula*, and the two others are characterized by high tropical species abundance and high upwelling indicators together. Overall, the average dissimilarity coefficient for the samples is close to 0.95, showing that non-analogy is generally not a problem for these samples. Furthermore, we note that down core the coefficient values do not follow a clear D/O pattern, so that our reconstructions are not systematically biased toward being better during one or the other episodes. Instead, we observe that coefficients are generally higher than average after 41 ka except during GIS7 and HE3, and generally lower than average before that date except during HE6, GIS15, GIS14 and GIS13.

[33] The SSTs calculated for MIS3 at site MD01-2444 show a marked contrast to the GRIP record and to the similarly detailed record obtained at ODP Site 1060 [*Vautravers et al.*, 2004]. The August SST shows increasing values toward the end of each Bond cycle, whereas the concept of the Bond cycle involves decreasing SST toward the end of each cycle as seen in the GRIP $\delta^{18}O$. At Site MD01-2444, the maximum SSTs are reached in the middle of the GIS16 interval, at mid GIS14, and during GIS11 and during GIS7. The evolution of SSTs during each Bond cycle is as follows: From a starting point during the HE we have a slow increase during either the first part of the first GIS or the first GIS of the cycle, then the SSTs culminate during the second GIS of the cycle before only reducing slightly again. In addition, the estimated SSTs were close to the modern values for most the time except during HEs. The warmest cycle is found during bc3 (41–47 kyr), in agreement with the lowest percentage of *G. bulloides* and *G. glutinata* found during that interval. Importantly, this record reveals that despite being easily and unambiguously aligned to GRIP using the planktonic $\delta^{18}O$, the SSTs off southern Portugal have a variability that looks more similar to the tropical hydrological signal that is recorded in the laminated sediments of the Cariaco Basin and that traces the ITCZ [*Peterson et al.*, 2000]. This suggests that the tropical climate (largely governed by ENSO phases) influences southern Europe in a more important manner than previously thought during the rapid climatic variability of MIS3. We notice that SSTs very similar to their present values were maintained for most of the time, even after HE4. Only after 32 ka does the area experience pronounced cooling for more than 1–2 kyr.

5.4. Lithic Ice-Rafted Detritus Events

[34] The lithic concentration (all lithics $\geq$ 150 μm) reaches 450 grains per gram of dry sediment during HE4. Lithics are also present in HE5, HE6 and HE3, although they never exceed 10/gram in any of these other stadials. In addition, HE4 contains a significant number of lithic carbonate particles. The first sample of the interval showing an important lithic carbonate event is concurrent with the anomalous light values recorded by the isotopes of *G. bulloides*, which together indicate the presence of fresher water from melting icebergs over the core site. Sample with maximum percentage of *N. pachyderma* (*sin*) (80%) is found in the same sample with the highest percent of total lithics (among lithic plus fauna). This peak in percent *N. pachyderma* (*sin*) is found at the end of the lithics rich interval so that it could indicate further cooling resulting from the MOC being reduced because of the icebergs melting. The extreme nature of HE4 has already been recognized in the pollen record of southern Europe [*Tzedakis et al.*, 2004].

6. Discussion

6.1. Heinrich Stadial Intervals

[35] Numerous studies have established that there is a tight link between events in central Greenland and characteristics of the surface ocean [*Ruddiman and Bowles*, 1977; *Heinrich*, 1988; *Bond et al.*, 1993; *Shackleton et al.*, 2000] so that in spite of dating uncertainties, paleoceanographers do not doubt that the GRIP GS/GIS events are reflected in coeval marine records. However, the amplitude of stadial

and interstadial temperature fluctuations over Greenland is approximately constant through MIS3, whereas in the tropical area [*Peterson et al.*, 2000; *Schulz et al.*, 1998] and at middle latitudes of the North Atlantic, typically in the Ruddiman Ice-Rafted Detritus (IRD) belt [*Labeyrie*, 2000; *Bond et al.*, 1999], the amplitudes differ. In these regions stadials corresponding to Heinrich events are more pronounced. Our work, thus confirms the broad view of MIS3 as discussed above in the northeastern Atlantic and, in particular, the SST results and the prominence of HEs relative to other stadials found by *Cayre et al.* [1999], *de Abreu et al.* [2003], and *Pailler and Bard* [2002]. In particular, cold faunal summer SSTs are estimated to have been lower by 10°C during HEs and by about 5°C from alkenone measurement [*Pailler and Bard*, 2002; *Martrat et al.*, 2004]. Among the three faunal groups that we have examined, the group *G. bulloides* plus *G. glutinata* traces the reinforcement of the northeasterly trade winds activity during each GS concurrent of HEs, and some other stadials, and therefore points to the extreme nature of HE stadials. This view is in contrast to the GRIP record where Heinrich event stadials are all equally cold. In addition, such a scenario implying an increase in the northeast trade wind intensity increase off Portugal calls for a reinforced NAO^{+} like situation.

[36] Our results for HEs and tentative link to NAO phases confirm what was inferred from a pollen study [*Sanchez-Goni et al.*, 2002] about changes in precipitation regime to the south of Portugal during MIS3, and by Uk'_{37} data [*Pailler and Bard*, 2002]. However, these last authors found lower productivity associated with HEs, which is not easily explainable if the upwelling was stronger. One explanation might be the occurrence of drastic changes in the structure of phytoplankton communities with, in particular, an enhanced production of diatoms during HEs, in opposition to GIS and most other D/O stadial intervals that would have been characterized by larger coccolithophoridae production. Evidence of such switching of types of main organisms produced has been provided in the Cariaco Basin through the study of chlorin steryl esters [*Dahl et al.*, 2004] during the Younger Dryas, when a more southerly ITCZ generated enhanced upwelling. The operation of a similar mechanism would need to be confirmed off Portugal. However, since increased percentages of *G. glutinata*, species feeding on diatoms [*Hemleben et al.*, 1989], are found during HEs this hypothesis seems realistic. Another element confirming the major impact of the northeasterly trade winds comes from the comparison of SST pattern in the western Atlantic at a similar latitude. For example in the Gulf Stream area [*Vautravers et al.*, 2004], outside the region of trade winds influence, SST records also show intensely cold HEs intervals when compared to other D/O stadials. As a result heat storage can occur at the western end of the subtropical Atlantic gyre while the MOC is reduced, as shown by detailed $\delta^{13}C$ measurements at Site 1060 that confirm the Caribbean Sea results of *Ruhlemann et al.* [1999] and *Huls and Zahn* [2000]. Finally, this study has confirmed the extreme nature of HE4, as was previously observed in southern Europe [*Tzedakis et al.*, 2004] and off Africa [*Zhao et al.*, 1995]. Beyond questions concerning with the actual amount of icebergs released during one or the other HEs, this paper points to the singularity of HE4 as the southernmost penetrating cold event, tracing the interval concurrent with the most intense NE trade winds of MIS3.

6.2. Other Stadials

[37] Now, we examine other D/O stadials and in particular their relative amplitude with respect to the much better known stadials containing Heinrich events. Except for the HE stadials, we have observed in core MD01-2444 that the coldest stadials are found after GIS15, GIS8, and GIS6. Although in the latter case it can be argued that this stadial is concurrent with a real Heinrich event as recently discovered by *Rashid et al.* [2003] it is discussed here. Despite the intensity of the stadial following GIS8 (based on percent of *N. pachyderma* (*sin*)) to be visible in core V23-81 on which correspondence of events with GISP2 was first proposed [*Bond et al.*, 1993], it has not been either clearly defined or frequently described. However, this major cooling and ice-rafting event was also noted the western Atlantic ODP Site 1060 [*Vautravers et al.*, 2004] as well as being also visible in the Uk'_{37} SSTs records of *Cacho et al.* [1999] and *Pailler and Bard* [2002]. In the [Fe] record at Cariaco Basin [*Peterson et al.*, 2000], it appears as one of the most intense decreases of the rain index and despite not being concurrent with a HE interval, the [Fe] reaches down to the level of a HE stadial. At site MD01-2444, the August SSTs reach at the time of this event (around 37 kyr) the level recorded for HEs (about 12°C), but the concentration of lithics are close to zero. In the same manner, the very low contribution of lithics carbonate in middle latitude cores [*Bond et al.*, 1999] seems to attest to the non-HE significance and non-Laurentide origin of this cold event. Therefore it seems unlikely that a regional response off Portugal might explain such a marked cold events after GIS8.

[38] Another intense cooling to the HE level (August SSTs drop of 10°C) is found before the onset of GIS5. This cold stadial is also visible in the tropical record of *Peterson et al.* [2000] and is marked in the Gulf Stream area [*Vautravers et al.*, 2004] by very low percent warm species pointing to a cold global event well before the end of the Bond cycle. An observation of importance that could confirm the existence of such an intense stadial (followed by long interstadial conditions, see next section) resides in the study of sea level changes [*Chappell*, 2002]. Chappell has found and dated a terrace in Huon Peninsula with a relative sea level change of +9 m that could correspond to a similar time interval identified as not coeval to the end of the Bond cycle, in contrast to other major terraces found at this site.

[39] Finally, another intense cold D/O stadial (SST record) appears just after GIS15, despite containing little IRD. This event is concurrent of a recently identified HE5a [*Rashid et al.*, 2003] provides a more regular pacing of HEs. It had previously been labeled HE5.2 [*van Kreveld et al.*, 2000], or tentatively identified as a remarkable event but not numbered in the middle North Atlantic [*Labeyrie et al.*, 1995]. Our study at site MD01-2444 confirms the importance of this event off Portugal. Furthermore, in this part of the record the resemblance between the [Fe] record

in Cariaco Basin [*Peterson et al.*, 2000] and our upwelling proxy (*G. bulloides* + *G. glutinata*) is striking. This resemblance points to the following situation: the ITCZ over the Cariaco Basin being in a southernmost position, a situation usually associated with ENSO and the maximal influence of the NE trade winds off Portugal, usually associated with NAO+ conditions. Outside the north Atlantic, a major event concurrent to the time of HE5a is also visible off Brazil [*Arz et al.*, 1998] where a wet event is also associated with an extreme position of the ITCZ. A prominent event is also recorded in the Arabian Sea [*Schulz et al.*, 1998], where it is associated with decreased summer monsoon conditions. Recently, *Higginson et al.* [2004] have proposed that strong El Nino situations coincide with low solar irradiance and that this explains monsoon variability at both interannual-decadal and millennial timescale. Therefore, in that perspective, HE5a, and by extension other major stadials (HEs as well as some other stadials as described in this paper) could be triggered by such a phenomenon.

6.3. Interstadials

[40] The main and most general result of the planktonic foraminifera study presented above is that off the southern part of the Iberian Peninsula the influence of the tropical climate was always strong during MIS3 and that the pattern of fluctuations is closer to the one recorded in the tropics [*Peterson et al.*, 2000] than to GRIP. In addition, the warmest SSTs were maintained near 20°C at quasi-Holocene level during most of stage 3. Interstadials were not very well individualized because cooling was largely restricted to short intervals (1.5 kyr) characterized by intense cooling (>8°C) and corresponding to HEs. Finally, SSTs decreased by more than 5°C for more than few thousand years only after HE3. Undoubtedly, this situation plays an important role in explaining vegetation changes over southern Europe as reported off Portugal, with indications of intense cold/dry spells during HEs mainly [*Sanchez-Goni et al.*, 2002]. However, beyond this regional analysis, it seems that our main result, as described in the above section supports a scenario of relatively unchanged climatic conditions during MIS3. This is consistent with evidence collected further to the north in central Europe in the form of dated charcoal layers that imply sustained woody environments during MIS3 [*Willis and van Andel*, 2004].

[41] Our study shows that GIS5 and GIS7 were unexpectedly warm interstadials. GIS7 was warmer (on the basis that it is poorer in *N. pachyderma* (*sin*)) than GIS8 at site MD01-2444 and at site V23-81, as well as at ODP Site 1060. Therefore we cannot consider the conditions occurring off Portugal as representing only a local response. For example in the bioturbation index in the Santa Barbara Basin [*Behl and Kennett*, 1996], GIS7 sediments seem more laminated than those of GIS8. The two arboreal pollen records off Portugal of *Roucoux et al.* [2001] and *Sanchez-Goni et al.* [2002] as well as two Arabian Sea records tracing increased monsoon variability [*Schulz et al.*, 1998], show a similarly pronounced event concurrent to GIS7 and point to a global event. Altogether, pollen evidence (increased percent of arboreal pollen tracing increased moisture during GISs), percent of warm species in core MD01-2444 tracing a warmer Azores current and a high rain index in the Cariaco Basin (pointing to a northerly ITCZ position [*Peterson et al.*, 2000], as well as the percent terrigenous component in core M35003-4 southeast of Grenada (GIS7 records a maximum for MIS3) [*Vink et al.*, 2001] could point to a tropical origin for this extreme GIS7 signal. This parallels with the high level of CH_4 recorded in GISP2 in comparison to GIS8 [*Brook et al.*, 1996]. Therefore GIS7 could be an extreme warm/wet GIS during which the production of CH_4 in tropical wetland would have been enhanced, but which for unclear reasons is not well recorded in the Greenland ice. This clearly needs further investigation.

7. Conclusions

[42] The polar front and polar waters in the North Atlantic did not influence the area south of 37°N except during HEs. With respect to polar influence and ice-rafting events, we find that the Bond cycles are not easily identifiable from our data and even seem to operate in a reverse manner during MIS3. Throughout each Bond, our study suggests a progressive subtropical warming concurrent with the polar cooling, which points to a climatic decoupling at the northern edge of the subtropical area during the last glacial. This situation allowed the southern part of the Iberian Peninsula to experience warmest months close to their current level until after HE3. On the basis of the clear match between upwelling proxies off Portugal and the [Fe] record in sediments of the Cariaco Basin, we propose a positive correlation between a NAO-like phenomenon as a driver of more intense, or possibly seasonally longer-lasting, NE trade winds and the positive phase of an ENSO-like situation that together imply dryer phases over the Caribbean Sea and off Portugal during HEs and some other stadials.

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M. J. Vautravers, British Antarctic Survey, High Cross Madingley Road, Cambridge CB3 0ET, UK. (mava@bas.ac.uk)